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THE PRINCETON WINDMILL PROGRAM

by

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FOREWORD

Princeton University has, in recent times, received a considerable amount of publicity - probably more than is yet deserved - for work with various wind machines. As a consequence there have been many inquires from other Universities, industrial organizations, governmental laboratories and private individuals from this country and from abroad. A great number of questions have naturally been asked, many of which are, at this point, not possible to answer; however, it is possible to respond to these sincere inquiries with a brief description of the origins, present status and future goals of the Princeton Windmill Program.

This paper is, then the answer to a distillation of the most frequently asked questions. It will be obvious to the reader that it is not a technical report in the usual sense but rather a report to the layman, intended to be as informative as possible within the limitations of present known, easily explainable technology.

The amateur or "back yard" builder is advised that this is not intended to be a "how to do it" manual; however, such a document is planned to be generally available in the not too distant future when actual accomplishments will permit authoritative descriptions and precise statements.

INTRODUCTION

The Flight Concepts Laboratory of Princeton University became interested in windmills as a direct consequency of the research performed over the years with the Princeton Sailwing. This device, first conceived as an advanced sail for a boat and later applied to a wing for aircraft use has attracted the attention of many able undergraduate and graduate students who have been largely responsible for its present rather refined status. The Sailwing is explained in more detail in the following section. It is, briefly a physically simple structure of light weight for its load carrying capability and has the aerodynamic characteristics of well designed rigid wings in the low speed range - up to approximately 150 knots. Above that speed there appears to be no reason why its interesting characteristics should not be maintained; however, its weight advantage might, depending upon design requirements, be somewhat reduced. Photographs of a Sailwing research airplane are shown in Figures 1 and 2. Because the Sailwing is simple and lightweight it is, therefore, inexpensive in comparison to more conventional wings. This economic advantage is compounded when one considers the greatly reduced dynamic effects of a light weight rotor on the ruggedness required of the supporting structure of a windmill.

The first of the Princeton windmills was constructed in 1966 using the then state of Sailwing art. It was a two blade axial flow type of machine of 10 ft. in diameter and is shown in the photograph of Figure 3. This windmill was intended as a purely research device to study the advance ratio characteristics of the blade at various blade pitch and blade twist angles. A secondary reason (but of considerable importance) for the machine was to enable the study of the behavior of the sails under all wind and weather conditions over the four seasons of the year.

The 1966 version of the Sailwing windmill was indeed tested over a one year period, withstanding, without damage, many periods of gale force winds, freezing rain and heavy snow storms. The structure, including the Dacron sails, appeared at the end of this time to have suffered no significant wear or other ill effects. This point is particularly made since many inquiries have been received relative to the survival characteristics of the device. A considerable amount of data, as yet unpublished, was accumulated from experiments with this windmill. During that time period it was thought that such a lightweight, simple and low cost machine might find application in many underdeveloped parts of the world. However, apathy toward this work existed until quite recently when moral and other support has appeared from some of the most unexpected quarters, which is, of course, most encouraging. Also during this time period, and up to the present, sailwing research continued which permitted the design of a second generation windmill which has recently been constructed and is shown in the sketch of Figure 4 and the photographs of Figures 5 and 6. It will be noted that the structure of this machine has been reduced to its essentials. During its first period of operation (Oct.- Nov.,1972) substantial quantitative data were obtained regarding its advance ratio characteristics. Also such qualitative characteristics as sail deformations, gryoscopic and other dynamic effects were studied. Since that time the machine has been undergoing modifications to further simplify its configuration, structure and cost. A sketch of this modified version is shown in Figure 7. The elimination of the tail boom and fin and the change from the "tractor" to the "pusher" configuration are the most apparent alterations. Other, more subtle, changes have also been made to improve its performance and operating lifetime.

The interests of the Princeton group extend beyond the classical windmill configuration and include wind machines of many types - some "too far out" for discussion here. There is one type deserving of mention at this time and that is the auto-rotating vane wind machine shown, schematically, in Figure 8.

It has been well known (from observations) for many years that a flat plate will, when pivoted about its mid chord axis, auto-rotate when subjected to sufficient wind velocity. A flat plate, however, will not always be self-starting (depending upon its stopped position relative to the wind) and, course, it will operate in either direction of rotation. To overcome both of these deficiencies it is only necessary to provide a geometrical asymmetry to the section as shown in the figure. The photographs of Figures 9 and 10 show a smaller version of such a device (vane size 5' high and 1' chord) mounted on a Chrysler automotive type alternator. The actual power output is not yet known but every indication is that it will be a usable quantity. Precise theory is not, at this time, available to enable the analytical prediction of the performance of this type of machine. However, theoretical work already begun at Princeton is expected to lead to valid analytical design methods. The auto-rotating vane wind machine is most interesting for several reasons:

a) Its performance is independent of wind direction (it is omni-directional).

b) It is simple, unobtrusive and inexpensive to construct.

c) The generator or alternator is mounted at the base of the machine thereby eliminating the need for slip rings.

For these very practical reasons it is felt that the scheme is worthy of pursuit and is therefore of some priority in the Princeton Wind Machine program.

DISCUSSION

As mentioned earlier the Princeton Sailwing as a wing for an airplane has been under research and development for many years, so in a sense the "homework" has been done on the basic device as applied to the airplane. Other applications now seem to be in order.

Figure 11 is presented to show the fundamental structure of the sailwing. It is seen from this figure that it consists of a rigid leading edge, tip and root section. The tip and root of the wing are connected by a trailing edge cable fastened to a wrapped around (two surface) sail. This sail is cut with a catenary arc trailing edge shape which enables chordwise tensions to be developed as a function of the tension in the trailing edge cable. Thus a taut wing may be constructed with no intermediate structure. The wing, though taut, is deformable with load and load distribution (velocity and angle of attack) which results in some most interesting and useful aerodynamic characteristics. Of most significance, however, is the lift and lift/drag behavior of the device insofar as application to the windmill is concerned. Figure 12 shows a comparison of the lift performance of the sailwing with that of a conventional metal wing of approximately the same aspect ratio. The quite high maximum lift coefficient, the steeper lift curve slope (initial) and the gentle stall are characteristic of the Sailwing. From Figure 13 it can be seen that the lift/drag characteristics also compare favorably with the conventional wing of similar aspect ratio. These two figures demonstrate that the fundamental aerodynamic behavior of the Sailwing is comparable to that of a sophisticated hard wing. Considering this and the fact that the Sailwing, for the same load carrying capability, is only one half the structural weight (and, therefore, cost) of the most inexpensive conventional wing, the logic of the Sailwing windmill becomes apparent.

The magnitude of the maximum value of the lift/drag ratio is one measure of an airfoil's efficiency and it can be shown that in the case of a windmill this L/D parameter directly affects the torque that the machine can generate. This can be seen by the diagrams of Figure 14. It can also be shown that by simple momentum theory (Reference 1) the maximum energy that can be extracted from the wind by an axial flow windmill cannot exceed 59% of the wind energy and this value can only be achieved by a rotor efficiency (η_R) of 100%. Of course a rotor efficiency of 100% is not a practicality. It is important to realize, however, that the power output of a given windmill is a direct function of the efficiency of the rotor. This, of course, refutes the oft-heard comment that the efficiency of a windmill is not important since the wind is free. One must consider many costs in the extraction of power from the wind. The three most significant are first cost, maintenance and depreciation costs. Thus, the higher the rotor efficiency the higher the power yield for a given wind machine and the lower the cost per unit of electrical power (watts).

Examples of the power output of two bladed windmills of the same geometry as the Princeton windmill but of varying sizes are shown in Figures 15 and 16. These figures are presented to indicate the magnitude of the power that can be extracted from the wind and not necessarily to suggest that large machines should be two bladed. As a matter of fact it has been traditional to limit the diameter of two bladed windmills to approximately 12 ft. because of gyroscopic effects. These actions which are generally dynamic in nature are due to the rotating mass of conventional rotors. Because of the light weight of the Sailwing rotor it has been possible to go to a 25 ft. diameter before dynamic effects become troublesome for a two blade machine. Even so, it is concluded from tests that a rotor of this size should have some symmetry as a rotating disc insofar as its mass distribution is concerned. For this reason two 90° radial arms and weights have been added to the rotor to achieve a "balanced moment of inertia" with the two blades - this, in effect, greatly reduces the variation in pitching moment as the rotating rotor turns in azimuth with varying wind direction.

For machines larger than 25 ft. in diameter it is felt that the number of blades should be greater than two to achieve the same dynamic results without resorting to mass balance devices. It is, obviously, true that the greater the number of blades the greater the starting torque and the lower the threshold wind velocity for starting. However, the greater the number of blades, the lower will be the overall rotor efficiency (η_R). The reduction in efficiency per blade, however, is quite small; therefore, the number of blades is more of an economic matter (considering first cost) than a technical problem. It is essential that adequate blade area be designed into the machine to absorb the maximum power of the wind for given design conditions.

It is interesting to note that the power output of such a machine can be stated as:

$$B\ HP = \frac{D^2 V^3 \rho \eta_R}{2200}$$

This is the expression that has been used to compute the power characteristics shown in Figure 15. This equation includes the term P_c which can be replaced in the terminology of this paper by, η_R, already defined. Of fundamental importance, however, is the necessity to understand that the power output of an axial-flow windmill is a function of the square of the rotor diameter and the cube of the wind velocity and, of course, of rotor efficiency, .

Figure 17 shows a wind map of the continental United States which indicates the average winds for a number of stations throughout the country. They are shown for both average winds and maximum recorded winds, the latter for at least a five minute period; of course, short period gusts could be even higher. An examination of this map indicates that the ratio of maximum to average winds is roughly a factor of six. This, of course, poses the most severe problem that a windmill must face - successfully - to be a useful power generating device. That is, the entire machine must have the structural integrity to withstand these natural forces. The design of a windmill to withstand only the average wind velocity would be quite simple and inexpensive, but when one considers the ratio of 6.0 between the average and maximum winds, and that dynamic pressure increases as the square of the velocity or, in this instance, a factor of 36, it is easily seen that the problem is somewhat more complex. There is, fortunately, a means of alleviating this tremendous build up of wind drag force upon the structure and that is by limiting the rotor RPM. Depending upon the blade pitch angle, β , the aerodynamic drag of a freely windmilling rotor can be as much as ten times that of the same rotor locked for zero RPM. If the blades were feathered (zero blade pitch) this ratio of ten could be even higher. Since the rotor is the dominant drag contribution to the entire structure, particularly for large windmills, it can be easily seen that this is where the drag control must occur. Thus, to insure both the survival of the machine and an economic structure rotor RPM must be limited above a given design wind speed. This can be done in several ways:

a) By simply building a braking system into the windmill which would be actuated by either centrifugal force, wind velocity or power output level.

b) By providing blade pitch control (articulated hub).

c) By providing blade twist control (in the case of the Sailwing).

Of these several methods the blade pitch control seems the least attractive; however, it is without doubt, the most effective.

The problem here in one of cost. Pitch control requires an articulated rotor hub which is expensive to construct and seems only justifiable for very large machines. For small and medium size windmills; perhaps up to 50 ft. in diameter, either the braking method or blade twist control seems to offer great cost advantages and at the same time permits a fully automated machine.

The problems associated with the conversion of the rotary motion of the windmill to the production of usable power are manifold but not extremely difficult to handle. The root problem is the need to gear upward from the relatively slow rotation of the windmill to the high RPM usually required for generators and alternators. This can, of course, be done at some bother and expense and will most probably require a centrifugal clutch in the system if conventional generators are used. There is, however, some hope that much, if not all, of this gearing might be eliminated by the use of the new technology of constant frequency alternators which permit a constant cycle output despite the input RPM. There will be, of course, a threshold speed below which the system will not be productive. Alternators of this type exist at this time and more appropriate machines are being presently developed.

Regarding the RPM that a given rotor of the Princeton type will develop as a function of wind velocity, a general rule of thumb is the value of 6.5 for the ratio of tip speed/wind speed for the free-wheeling windmill. For maximum power output this value is presently estimated to be 4.5; however, experimental confirmation of this number has not yet been made. These values should be applied to the general configuration shown in the Figures of 4, 5 and 6 which is a two blade machine of aspect ratio (per blade) of approximately 6.0.

Some comments should be made regarding energy storage since a windmill itself is but one component of a total system if it is to serve a useful function. First of all it should be understood that the Princeton group, while most interested in unique energy storage systems, does not pretend to have expertise in this area. Traditional methods such as storage batteries and pumping water to an elevated reservoir are well understood by most persons. More subtle, however, are quite advanced systems presently under investigation in other institutions. For the present, Princeton leans quite heavily toward the conventional wet-cell battery as a reasonable method of energy storage.

The investment in storage capacity seems to be directly related to the constancy of the winds and thus the geographical location of the wind machine. Consider a location of a windmill on one of the Carribean Islands or in other parts of the world where the trade winds are highly reliable, night and day. In such a case but little energy storage capacity would be needed. However, in most parts of the civilized world this happy condition does not occur, therefore, despite a high average wind the storage capacity required will increase with the inconstancy of the wind. It is fortunate that for many parts of the earth nature with her winds and man with his technology seem to conspire to provide a source of reasonably economic energy to serve the need of a great many people.

EPILOGUE

It is hoped that this simple paper might serve to answer some of the many questions that have been posed in recent months regarding this fascinating field. Where the enclosed material has failed to satisfy the reader it is because, surprisingly, much research and development remains to be done. In addition, the author must confess to ignorance beyond the limits of each point discussed.

Reference:

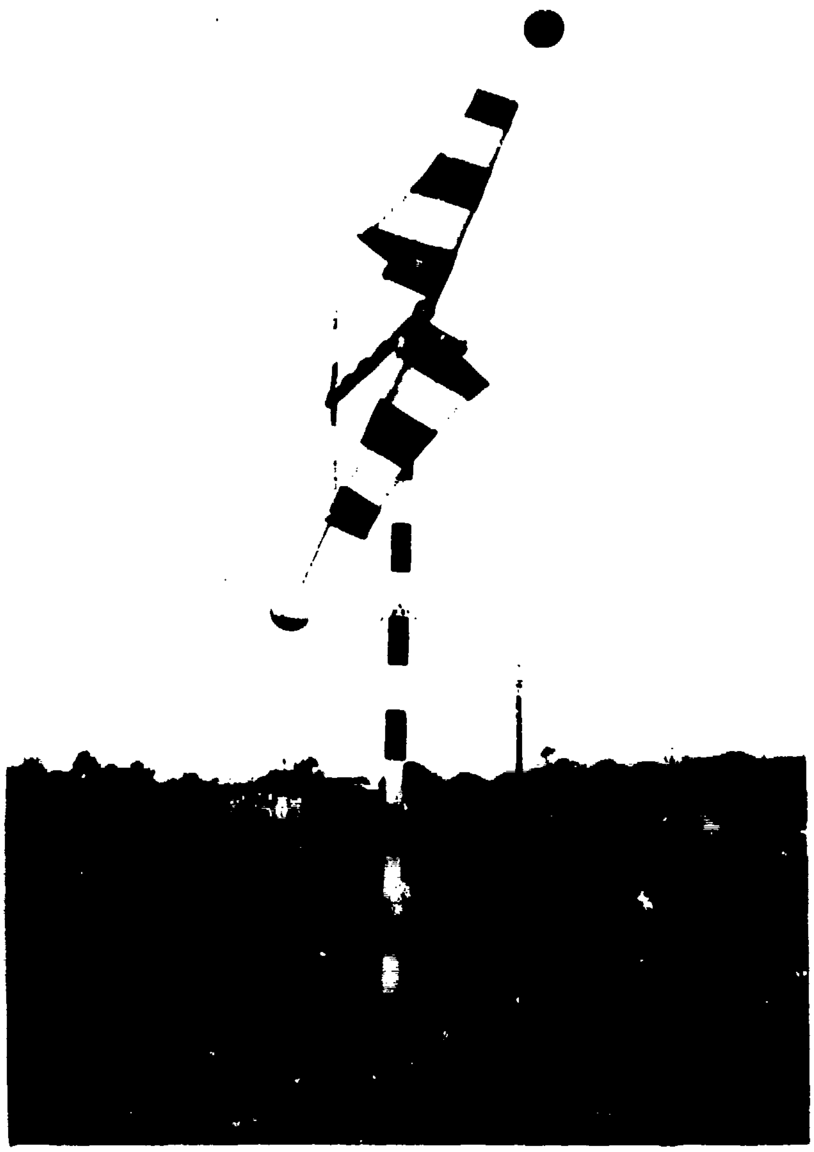
Banmeister, Theodore, Editor in Chief, Mark's Standard Handbook for Mechanical Engineers, McGraw-Hill Book Co., New York, 1967.

Note:

The application of the Princeton Sailwing to a Windmill is covered by U.S. Patent No. 3,597,108.

Figure 1

Figure 2



1966-10 ft. Dia. Sailwing Windmill

(Note: Spheres mounted on blade tips are for torque measurements)

Figure 3

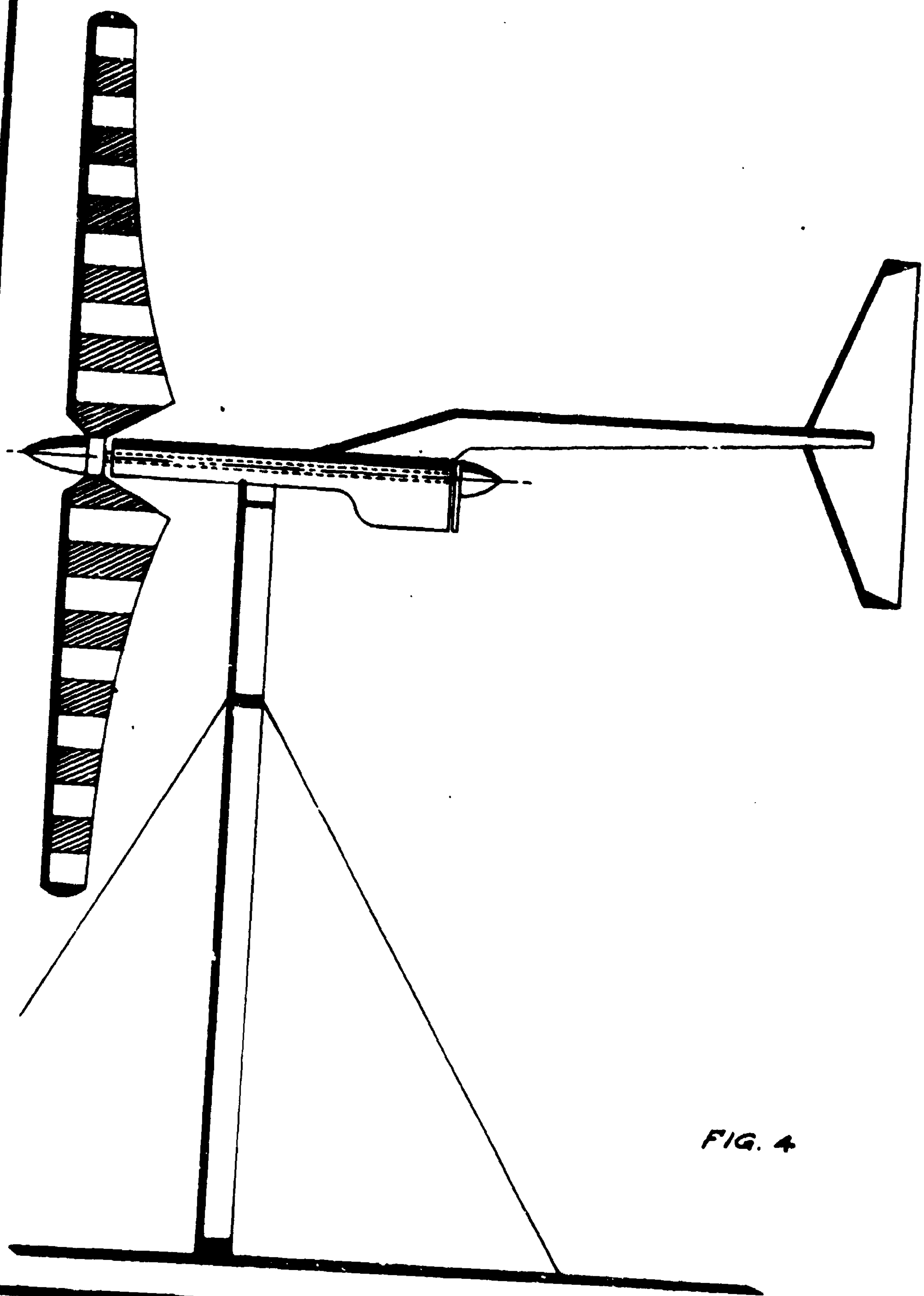
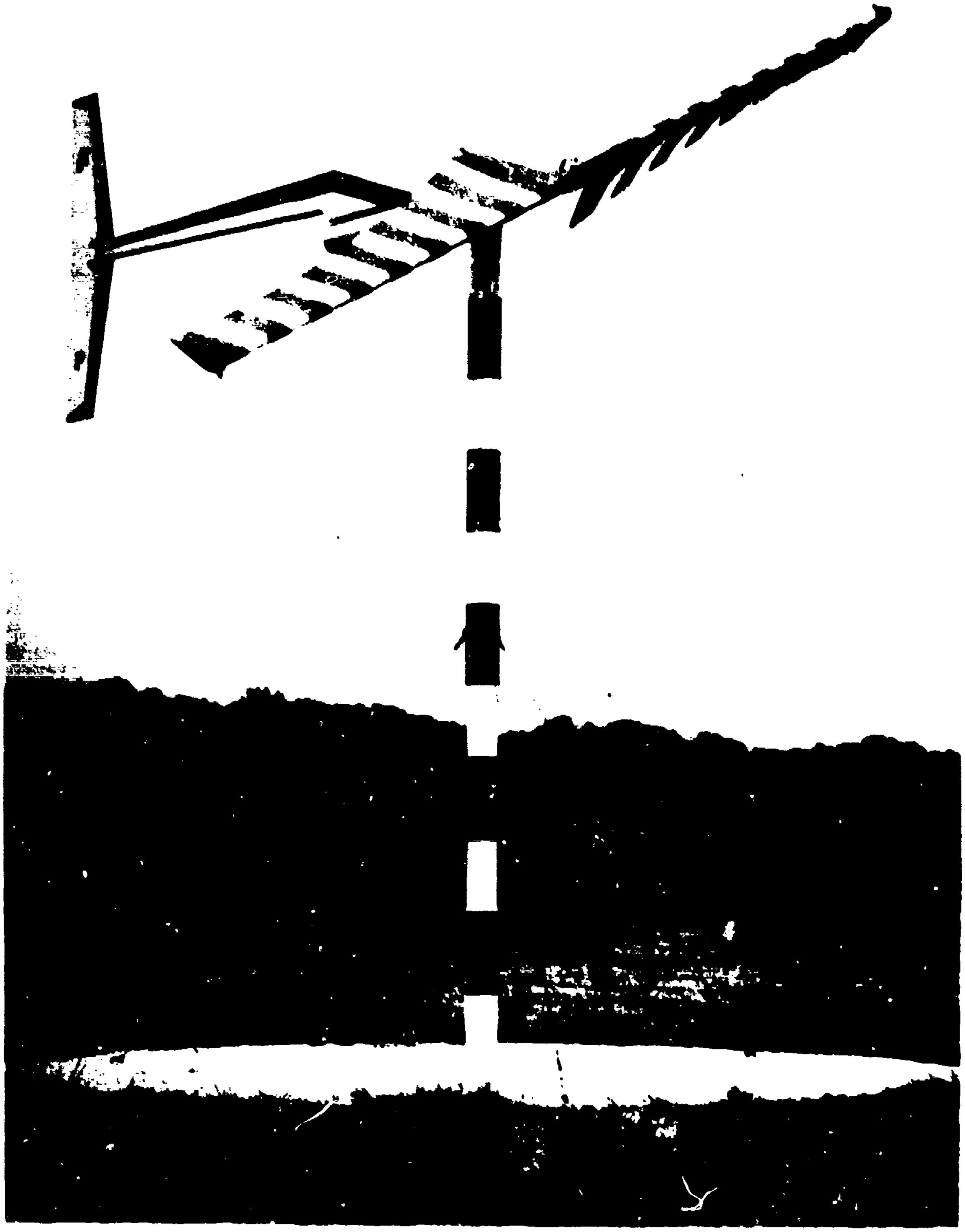
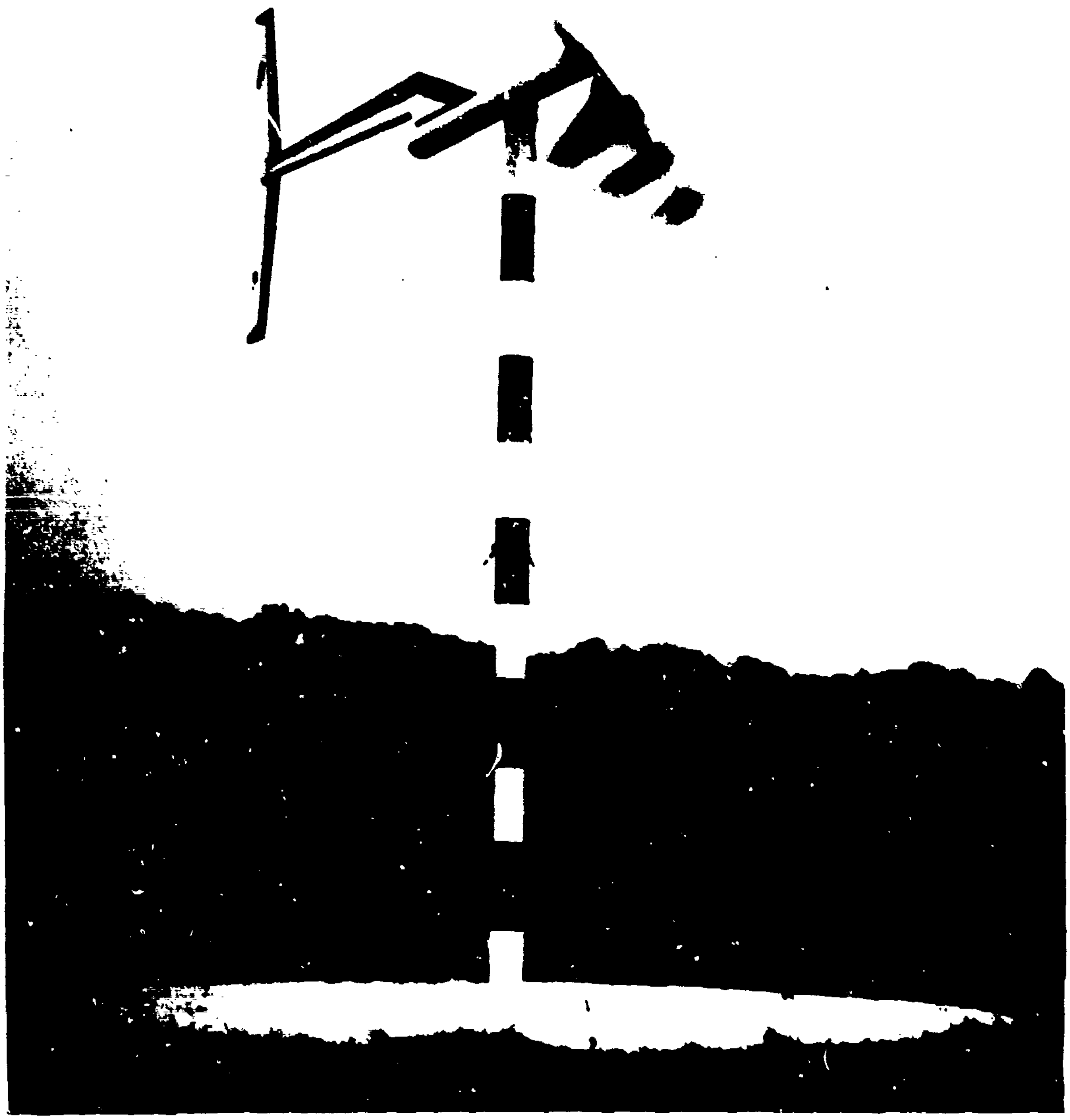


FIG. 4



1972-25 ft. Dia. Sailwing Windmill

Figure 5



1972-25 ft. Dia. Sailwing Windmill

Figure 6

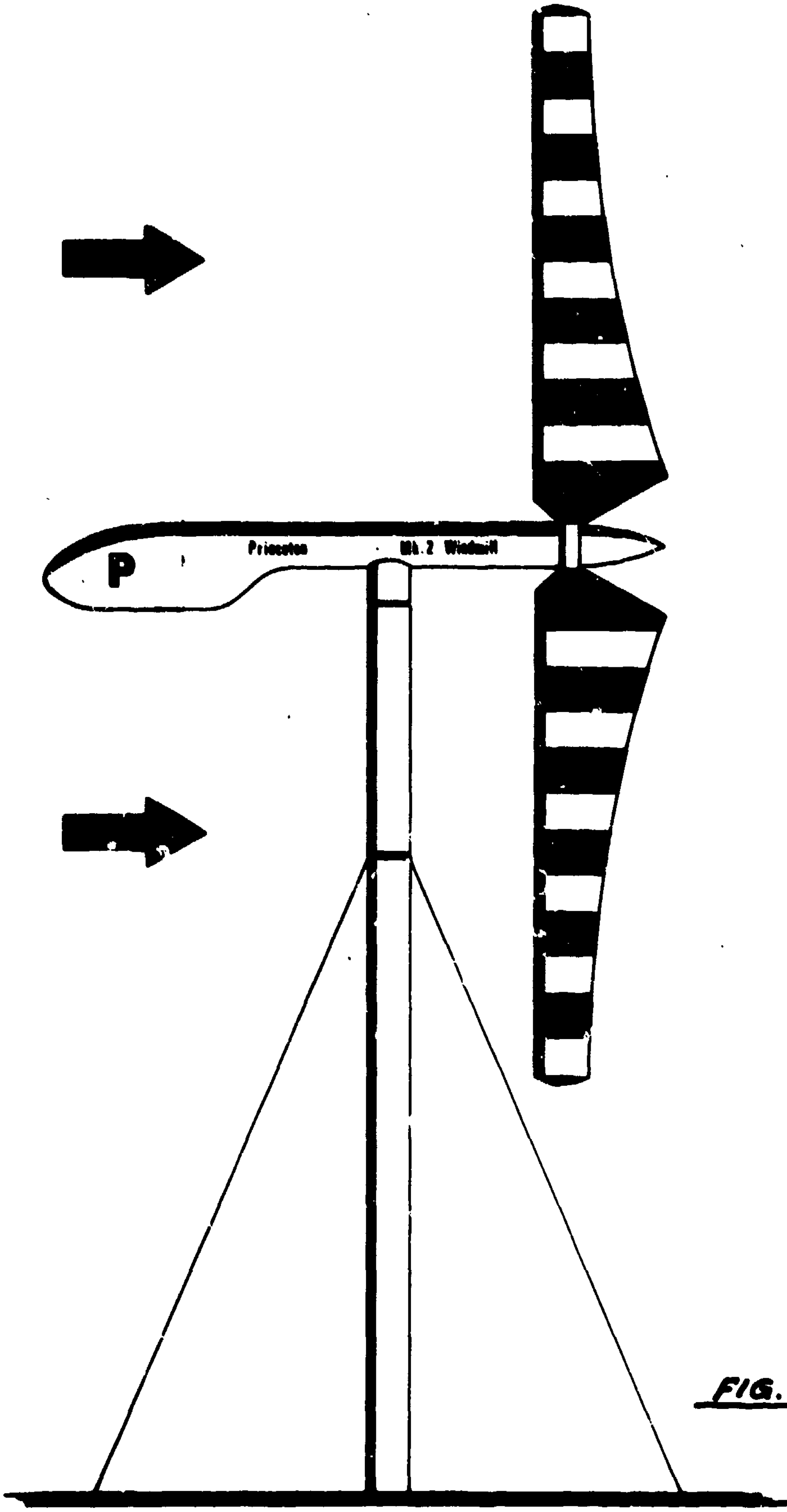
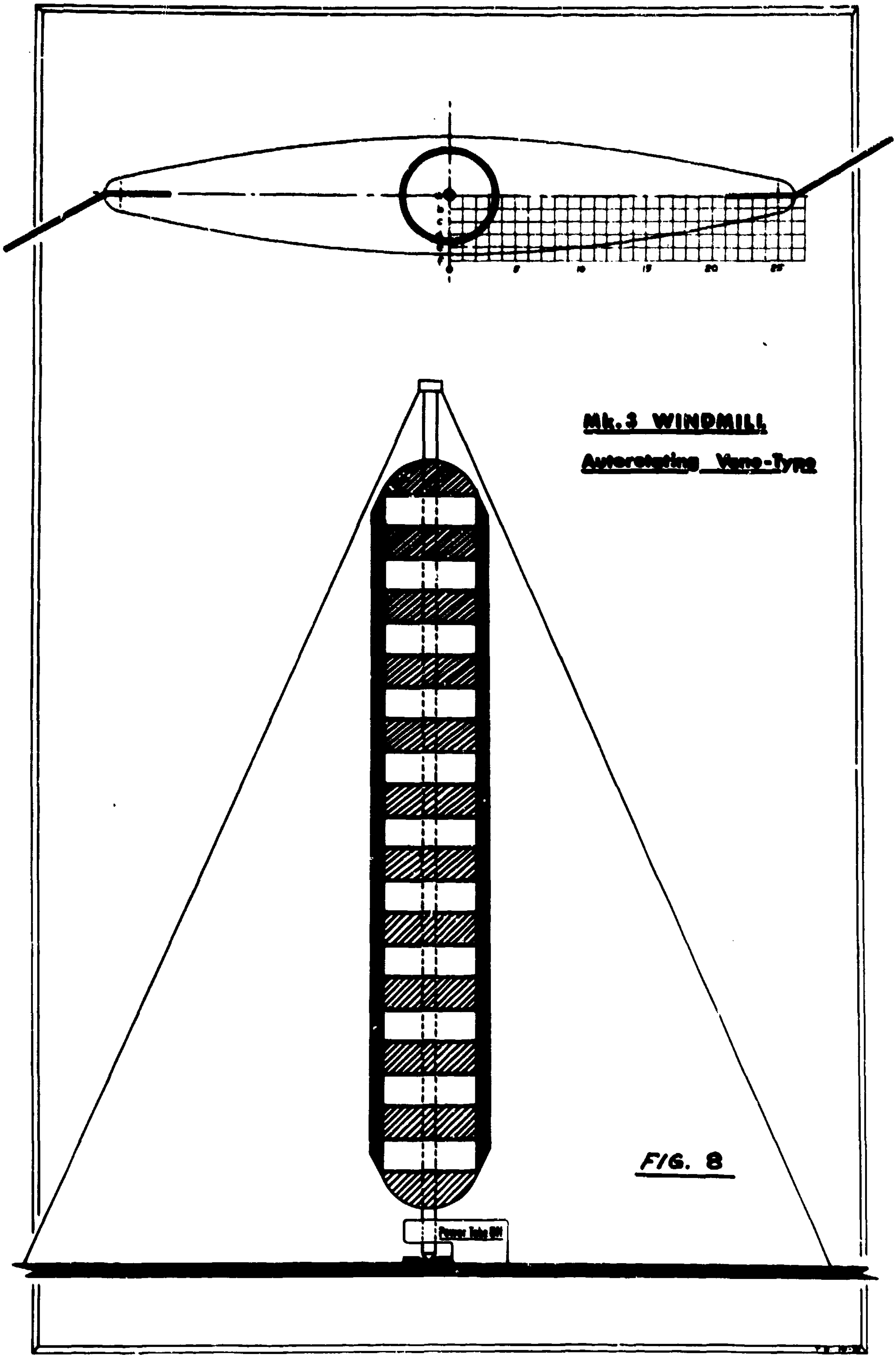


FIG. 7



Mk.3 WINDMILL

Autorotating Vane-Type

FIG. 8

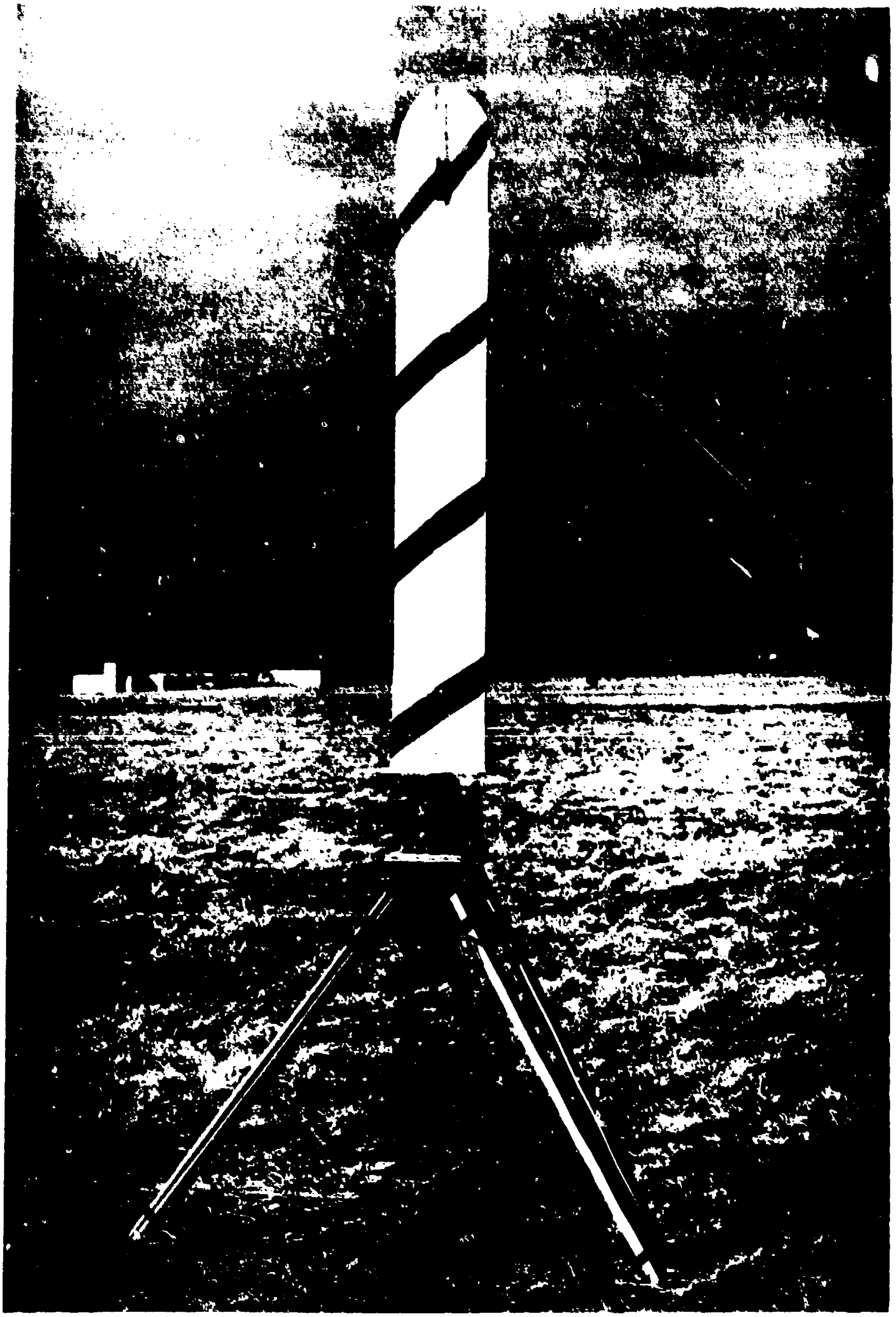


Figure 9

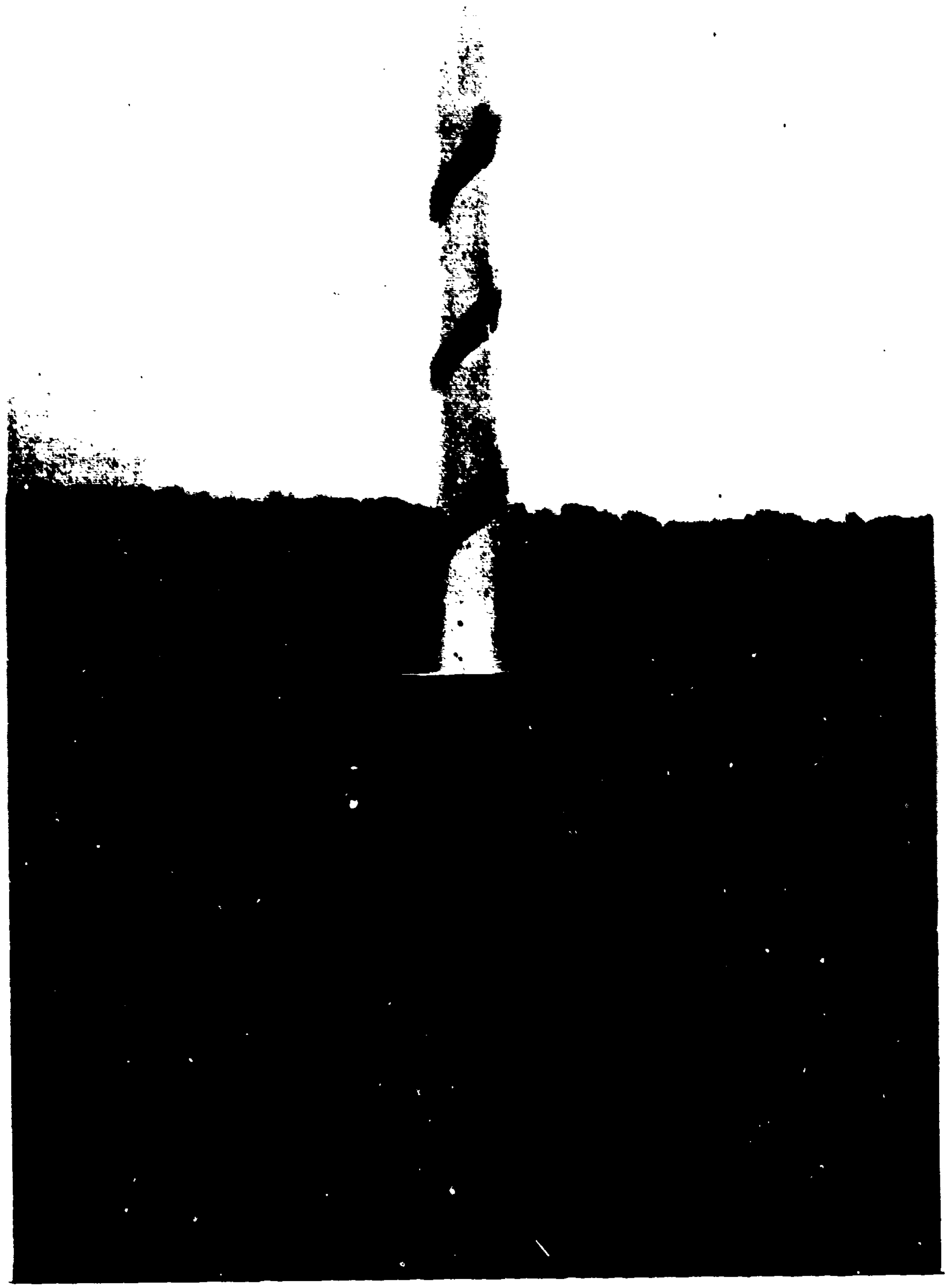
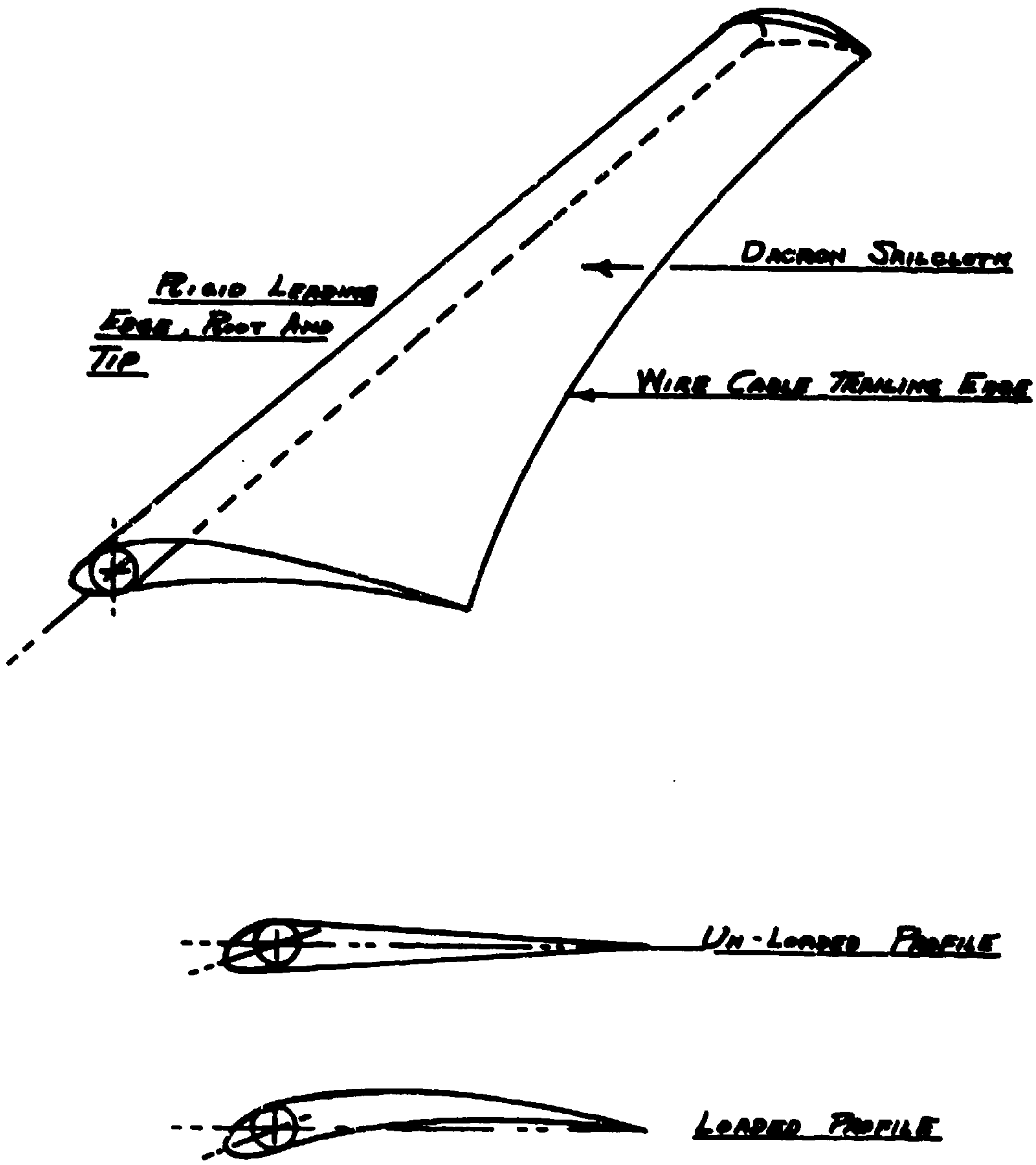


Figure 10

FIG. 12



RIGID LEADING EDGE, ROOT AND TIP
DACRON SAILCLOTH
WIRE CABLE TRAILING EDGE
UN-LOADED PROFILE
LOADED PROFILE

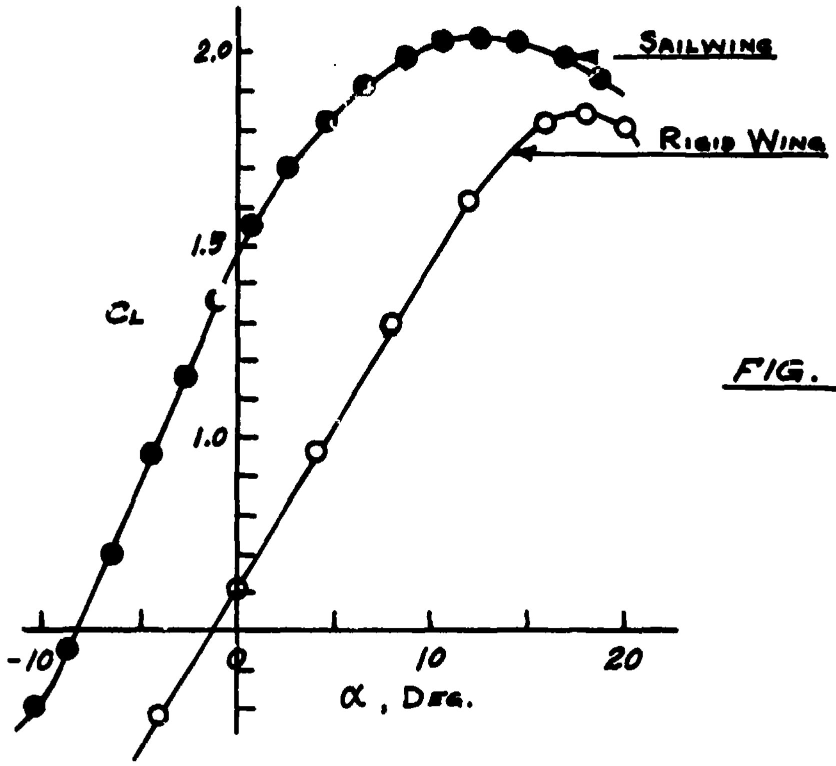

SAILWING
RIGID WING
2.0
1.5
1.0
C_L
-10
0
10
20
α, DEG.

FIG. 12

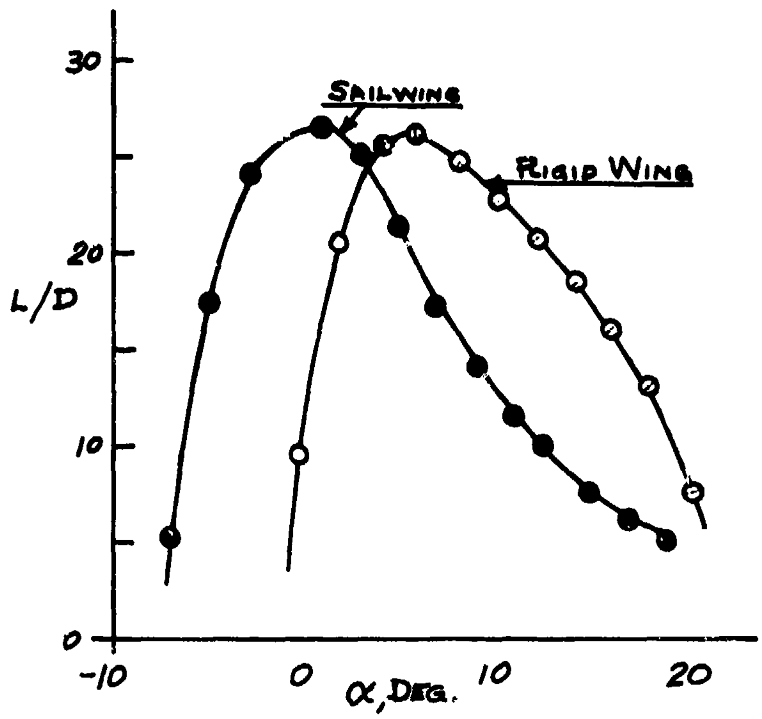

SAILWING
RIGID WING
30
20
10
0
L/D
-10
0
10
20
α, DEG.

FIG. 13

A.) HIGH L/D AIRFOIL SUCH AS SAILWING OR WELL DESIGNED RIGID BLADE

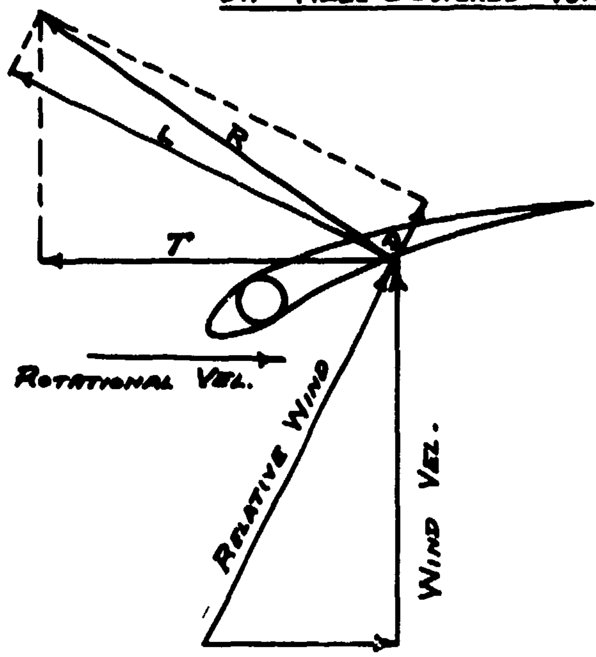
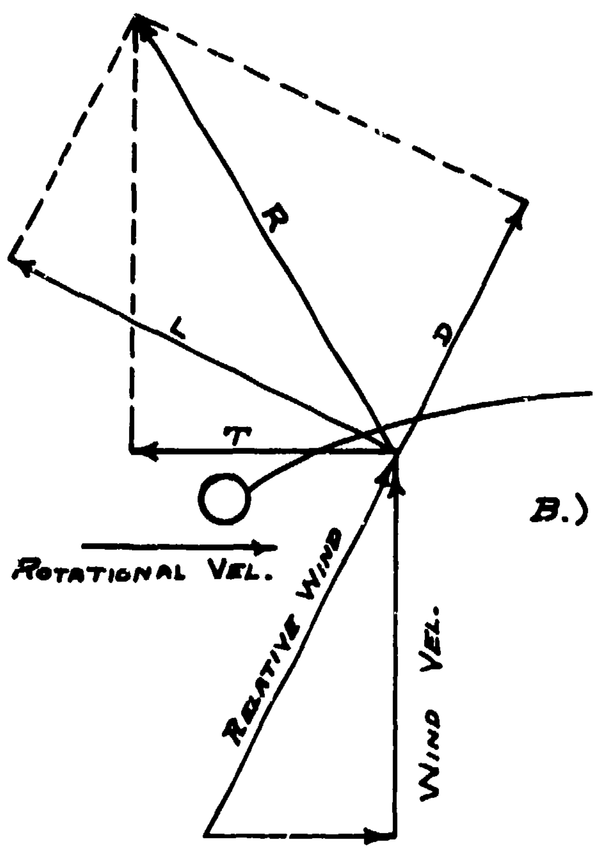


FIG. 14

WHERE : L = LIFT FORCE
D = DRAG FORCE
R = RESULTANT FORCE
T = IN-PLANE FORCE FOR TORQUE DEVELOPMENT



B.) LOW L/D AIRFOIL SUCH AS SIMPLE SAIL OR LOW EFF. AIRFOIL

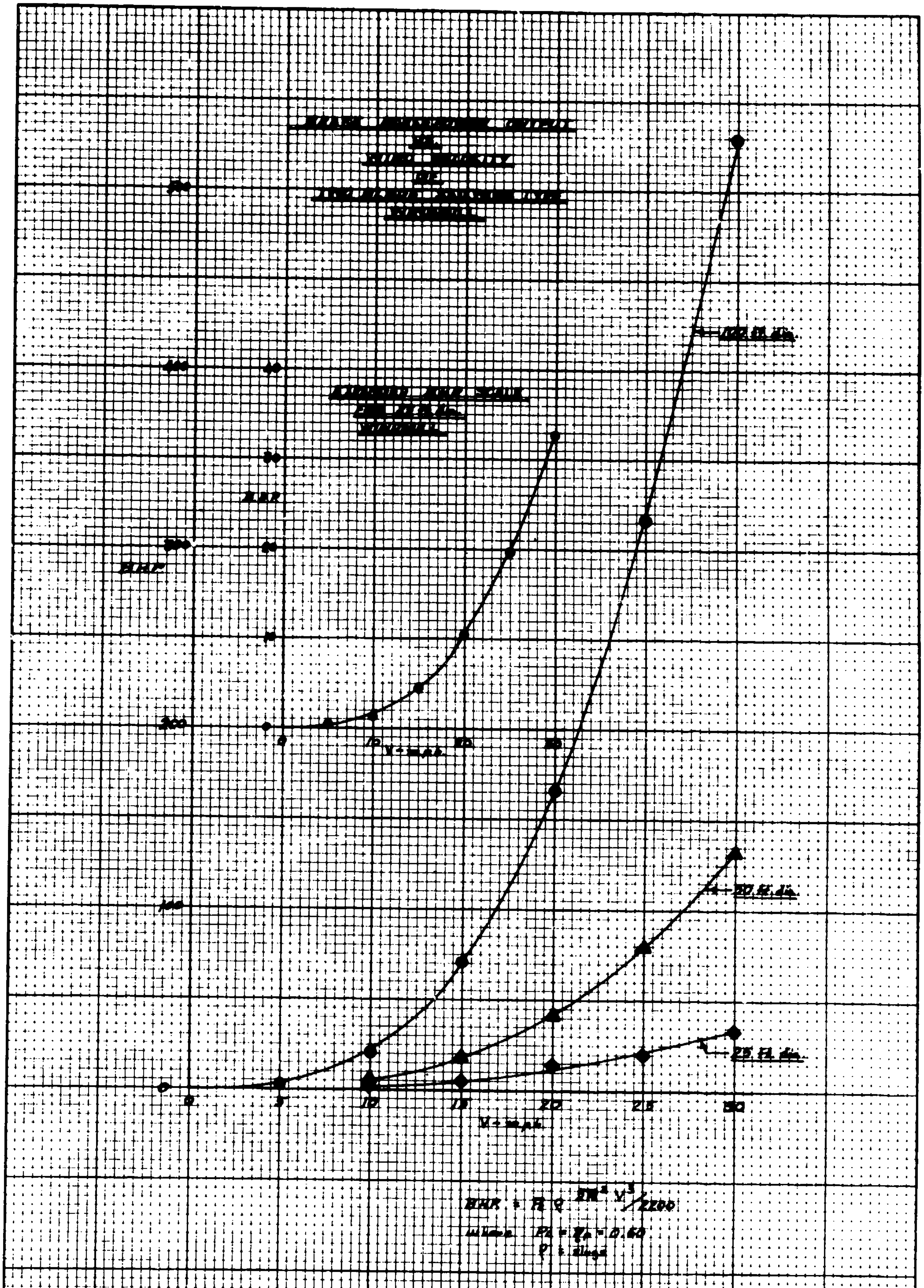


Figure 15

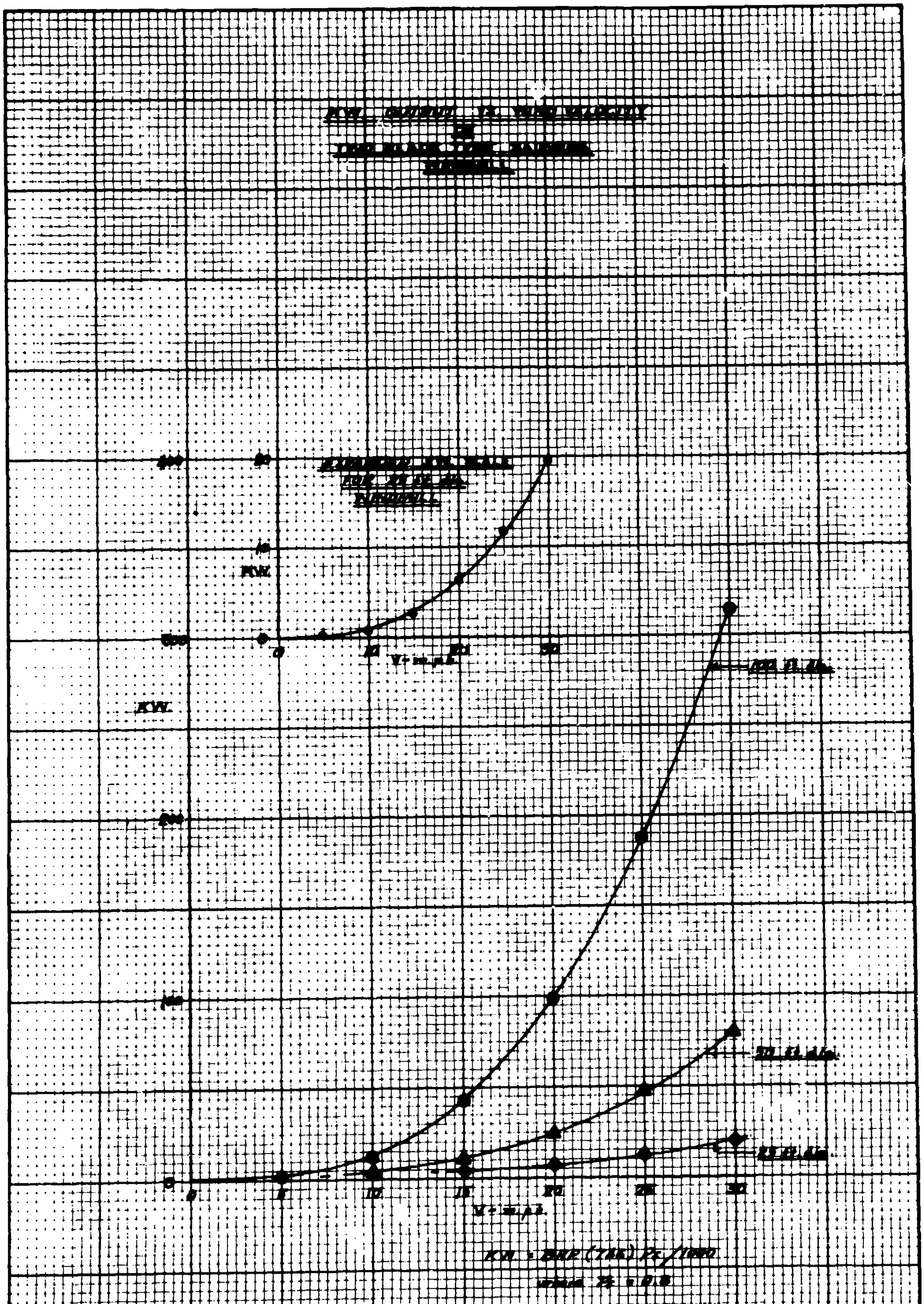


Figure 16

Average And Maximum Winds

Continental U.S.A.

(m.p.h.)

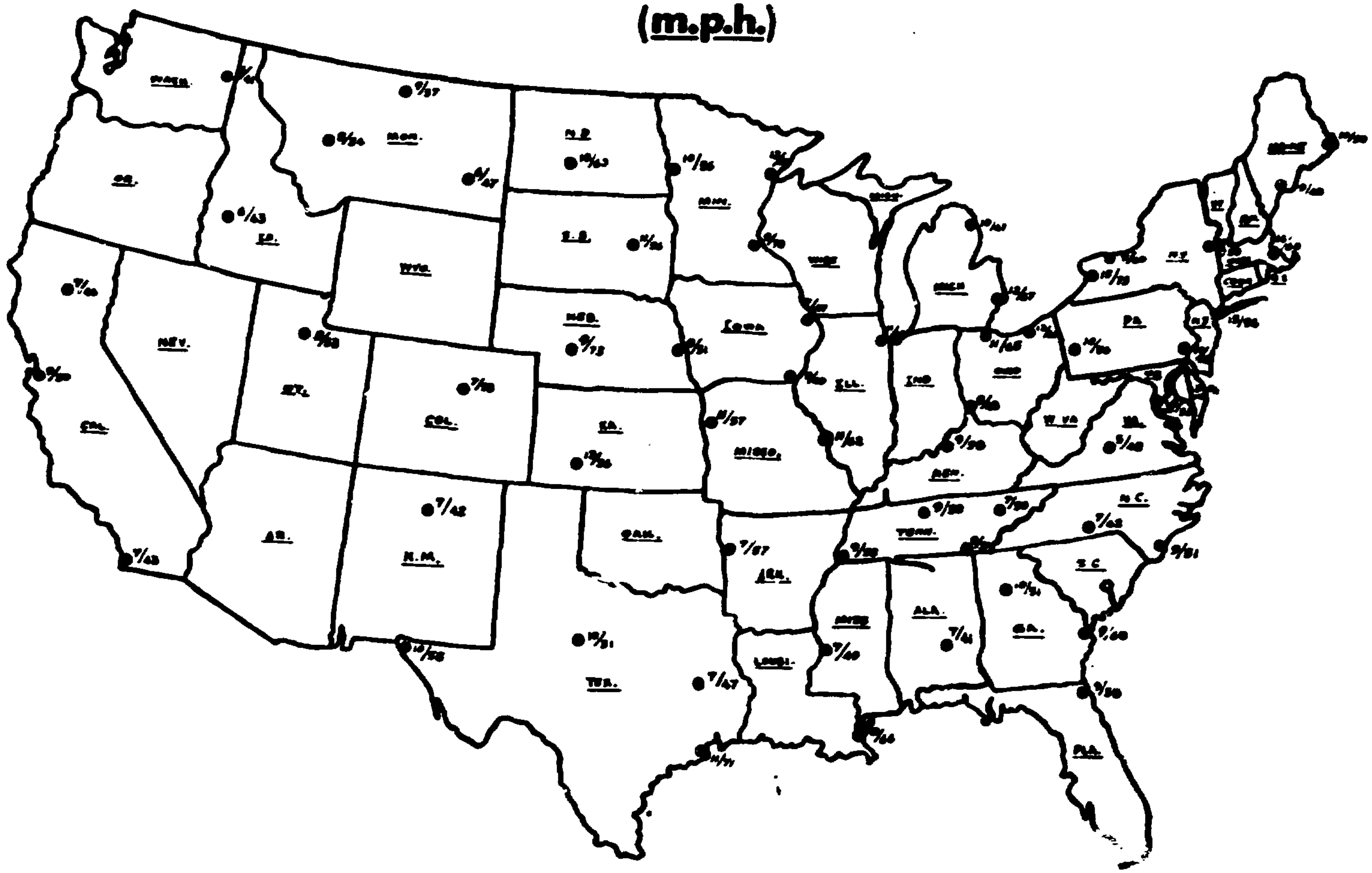


Figure 17